A Combined Analytical and Experimental Study on Inflatable Booms

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Abstract—Development and infusion of breakthrough technologies is needed to enable better, faster and cheaper space missions to be flown in the future. One of these technologies, the space inflatable structures, is currently receiving much attention. The use of space inflatable structures can potentially revolutionize the architecture and design of many large, lightweight space systems that must have extremely high packing efficiency at launch and be reliably deployed in space. Examples of these systems include sunshields, solar arrays, solar sails, telescopes, concentrators, and space radar antennae. To facilitate effective designs of these space inflatable systems, the behaviors of their fundamental, building-block structural elements, the inflatable booms, need to be thoroughly characterized and understood. This paper presents experimental and analytical study results on different types of space inflatable booms, including the self-rigidizable carpenter-tape-reinforced aluminum laminate booms.

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1. INTRODUCTION

For most space inflatable structural systems, the basic building-block structural elements are long, tubular beams and struts that are commonly known as inflatable booms. When being stowed for launch, these inflatable booms are generally flexible and can be rolled up or folded up to achieve high packing efficiency. After reaching the desired orbit, the stowed booms will be inflated and deployed by internal pressurization to attain their stiffness and design configurations. For a space mission that lasts only a few days, post-deployment rigidization may not be needed and maintaining a constant internal pressure will stabilize the booms. However, for missions of longer lives, it is necessary to rigidize the deployed booms by using one of many space rigidization methods for long-term space survivability. Therefore, depending on the need of space rigidization, a space inflatable boom can be classified as either a pressure-stabilized boom or an inflatable rigidizable boom. The pressure-stabilized booms are typically constructed with thin polyamide films or urethane-coated fabrics. On the other hand, a space rigidizable boom can be further classified as resin-rigidizable or self-rigidizable. A resin-rigidizable boom typically consists of three elements, the bladder, fabric layer and outer enclosure. See Figure 1.

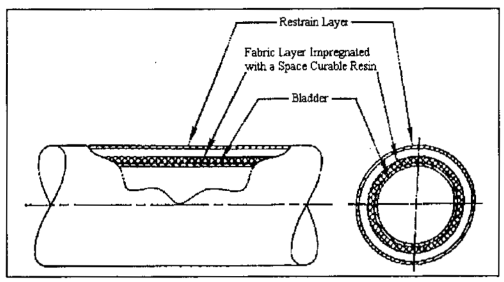

Figure 1. Typical construction of resin-rigidizable inflatable booms

The bladder and the outer enclosure act as pressure barrier and ronstraining layer, respectively. The fabric layer (or layers) of a space inflatable/rigidizable boom is commonly made of woven graphite, Kevlar, or Nylon fabric and impregnated with a space-curable resin such as hydro-gel, thermal set, or UV-curable. The self-rigidizable booms, typified by those constructed with aluminum laminates (see Figure 2a) do not rely on the use of space curable resins. An aluminum laminate boom will be subjected to two-step inflation pressurization in space. After being deployed by the first inflation, the boom will be subjected to a second inflation at higher internal pressure and its aluminum layer is stretched beyond the material yield point (see Figure 2b). After the inflation pressure is vented, space rigidization of the aluminum laminate boom is achieved by deriving stiffness from plastic deformation of the aluminum layer. Due to many inherent advantages, such as not requiring space power, low contamination and out gassing, and simpler construction, the aluminum laminate booms have received much attention for application to future space missions.

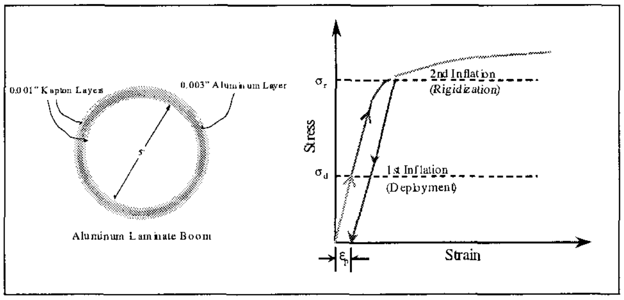

Figure 2. Self-rigidization based on strain hardening of aluminum laminate

The needs for structural characterization of the pressure-stabilized booms, the resin-rigidized boos, and the aluminum laminate booms are different. For the first two, the major structural concern is related to when the boom is being inflation deployed, as well as when it is fully deployed but not yet rigidized. One the other hand, the major structural concern of the aluminum laminate booms is its relatively weak post-rigidization stiffness and strength – both of which are difficult to model and predict. The objectives of this research effort are to address these identified concerns of space inflatable booms by performing laboratory tests and to use the obtained test data for correlation with analytical modeling and predictions. It was also during the course of this experimental/analytical study that an innovative type of aluminum laminate booms was developed. This new type of self-rigidizable booms called the carpenter-tape-reinforced aluminum laminate booms, have greatly improved load-carrying capabilities and require a much lower inflation pressure.

2. Material Tests

The experimental portion of this study started with testing material coupons to obtain stress-strain curves. Test materials include urethane-coated Nylon fabric, aluminum sheet, and aluminum laminate that are commonly used for the construction of inflatable booms. Test results were used to determine the mechanical properties of these materials. 1" x 6" coupon specimens were prepared and used to acquire force-verses-elongation data, which were later converted into stress-strain curves. Figures 3 shows a coupon being tested on the tensile machine.

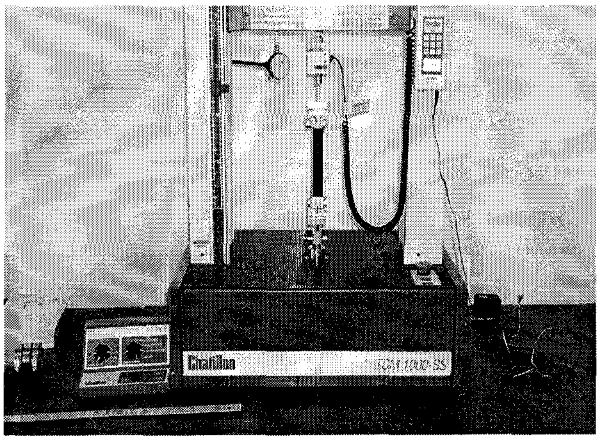

Figure 3. An urethane-coated Nylon coupon on the tensile machine

Figure 4 is a typical strain-stress curves of Urethane-coated Nylon. Anisotropic behavior (i.e. directional dependent properties) of this material was observed. Figure 4 also shows the hysteresis loops of urethane-coated Nylon when loaded in two mutually perpendicular directions.

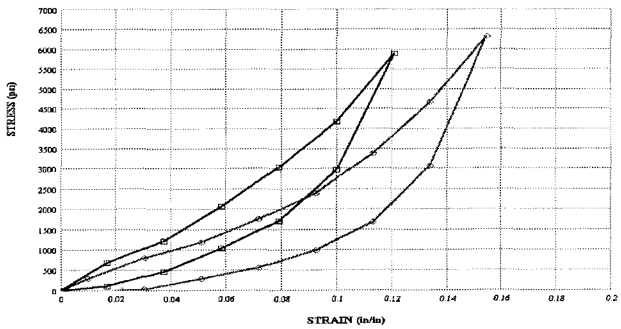

Figure 4. Strain-stress curves of urethane-coated nylon loaded in two mutually perpendicular directions

Figure 5 presents a typical stress-strain curve of the 3-mil-thick aluminum laminate. This laminate is fabricated from a 3-mil 1145-0 aluminum sheet with a 1-mil polyester films glued on each side. It was noticed that at about 20% of straining the films started to separate from the aluminum layer. The separation might be caused by the shear stresses buildup between the aluminum and the films. When running tensile tests repeatedly, it was observed that the loading rate significantly influenced the stress-strain relationship. To obtain consistent test results, a very slow rate of loading was used and kept constant.

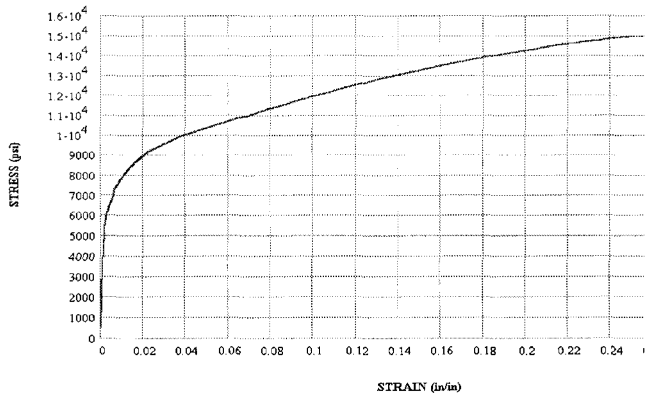

Figure 5. Stress-strain curve for 3-mil aluminum laminate

3. Pressure-Stabilized Booms

Pressure-stabilized booms made of urethane-coated fabric materials, such as Nylon and Kevlar have been used to assemble space inflatable structural systems. Examples include the three 100-foot-long urethane-coated Nylon struts used in the Inflatable Antenna Experiment [4] and the urethane-coated Kevlar frame of an inflatable synthetic-aperture radar (SAR) engineering model [5]. The pressure-stabilized inflatable booms, which are highly flexible before reaching the fully inflated state, behave very differently from their conventional rigid counterparts. Structural behaviors of pressure-stabilized inflatable booms have been investigated by several researchers [e.g., 1, 2, and 3]; however, the mechanics by which an inflatable boom derives its structural integrity from internal pressure needs to be further studied and understood. As pointed out by several previously conducted studies [6, 7, and 8], a pressure-stabilized boom derives its stiffness from tensioning of the fabric materiel. Strain energy stored in the fabric wall of the boom due to internal pressurization plays an important role in generating bending stiffness, called the differential stiffness [9]. The present research attempted to establish the relationship between bending stiffness and internal pressure for the pressure-stabilized booms.

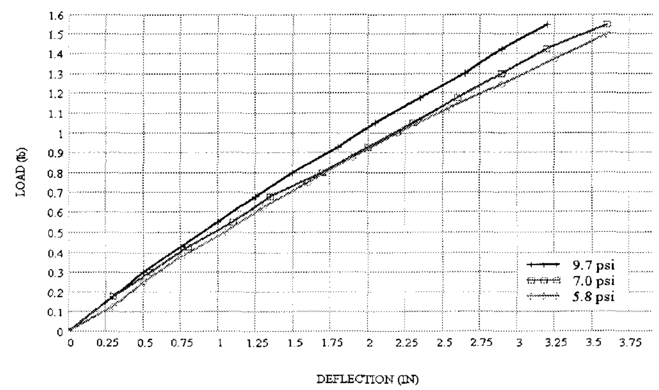

Figure 6. Deflections at the free end of the boom at various pressure levels and loads

Several 4"-diameter and 43"-long urethane-coated 12-mil-thick Nylon booms were fabricated and used as test samples. Each boom was set up as a cantilever beam with a concentrated load applied at the free end. Bending tests at different boom internal pressures were conducted to examine the effect of pressure variation. Deflections at the free-end of the boom at various pressures were measured as the function of applied loads. The results are shown in Figure 6.

A finite element model was also assembled to simulate the pressure-stabilized boom being tested. For a finite element computer program to accurately predict the behavior of an inflatable structure it must have good non-linear analysis capabilities to handle large deformations and to account for the stiffening effect in the fabric due to pre-stresses induced by internal pressure. Also, it must have the ability to treat fabric materials, which means no bending stiffness or compression stiffness is allowed. DYNA-3D, a non-linear explicit finite element analysis code was selected to perform the analysis. The DYNA-3D model contained 2,765 nodes and 2,763 elements to closely approximate the geometry. Figure 7 is a plot of the model.

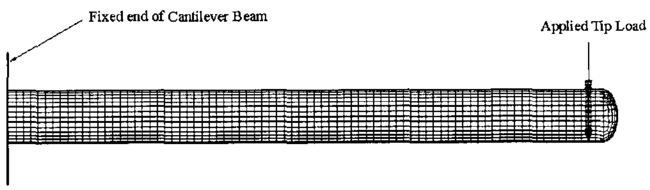

Figure 7. Finite element model of pressure-stablized boom

The boom was constrained such that all degrees of freedom of the nodes at the wall were fixed to simulate the fixed end condition. Approximation of the tip loading condition was accomplished by distributing the applied load at 32 nodes forming a circular cross-section at the free end. The equivalent concentrated nodal loads perpendicular to the inside wall surface were used to simulate the internal pressure in the boom. The analysis code solved for the displacements at all nodes. Selected nodes along the top surface were used to compare with the experimental data. Computer simulations were run for a wide range of test conditions by changing the inflation pressure or the applied tip load. Figure 8 shows the computer simulation results for the test condition in which a one-pound tip load was applied on a boom inflated to 9 psi.

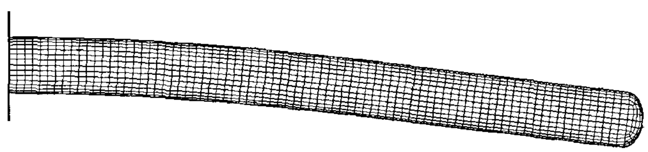

Figure 8. Finite element displacement results

In order to compare the simulation results to the test data, both analytically predicted deflections and experimentally measured displacements were plotted over the entire length.

Figure 9 compares the analytical and experimental results for 1.0- and 1.5-pound tip loads. For both loading cases, internal pressure of the boom was kept at 9 psi. It is observed that the test boom deforms less than that predicted by the finite-element analysis model. This may partially due to the inability of the analysis model to handle the non-linear materials properties, which are functions of strains in the fabric wall of the boom.

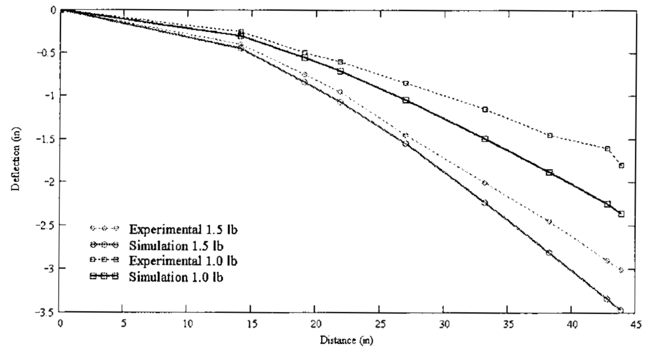

Figure 9. Boom displacement results for 9.0-psi inflation pressure

4. INFLATABLE/RIGIDIZABLE BOOMS—STRETCHED ALUMINUM LAMINATE BOOMS

Because of the impacts of micrometeorites, small holes will be created on inflation-deployed booms and gas leaks are unavoidable. This means that make-up gas needs to be constantly supplied to keep the boom fully inflated during the entire mission. Therefore, the non-rigidizable pressure-stabilized booms are usually not suitable for long term space missions. As a result, post-deployment rigidization is required for long-term survivability of space inflatable booms. Currently, several space rigidization methods are being developed [5], including hydro-gel resins; thermal set resins (heat rigidization), UV-cured resins, thermal plastics (cold rigidization), and stretched aluminum laminates. Among these methods, only the stretched aluminum laminates method is self-rigidizable; that is, no power or other curing catalyst is required for rigidization. Component materials of stretched aluminum laminates, aluminum and polyamide films such as Kapton also have long space heritage, are space qualified and proven to have very low in-orbit outgassing/contamination. This section presents our study results on the buckling capability of stretched aluminum laminate booms.

It is well known that the buckling capability of any long boom under compressive loading is proportional to the design parameters of boom thickness and the modulus of elasticity of the boom material. However, these two design parameters must be limited in such a way that the boom can still be rolled up for stowage. It was found that for aluminum laminate booms, the optimal thickness of the aluminum layer is about 2 or 3 mils. Therefore, the 2-mil and 3-mil aluminum laminates were studied in this research effort.

Basically, aluminum laminate booms make use of the strain-hardening characteristics of the soft aluminum layer for self-rigidization. Figure 10 represents the strain hardening of 2-mil-thick 1145-0 aluminum sheet at different percent strain. Coupon specimens (1" x 6") of this material were tested by slowly tensioning to 2% elongation and followed by slow release of tensioning force. Then the test was repeated again to generate a new stress-strain curve. The slope of the new curve represents the modulus of elasticity of the strain hardened material. The same test was performed for 3% and 4% elongations to obtain the results shown in Figure 10. From this figure one can conclude that the modulus of elasticity is proportional to the percentage of elongation. That is, a higher percentage of elongation yields a higher modulus of elasticity for strain hardened aluminum sheet. Theoretically, higher modules of elasticity should yield higher buckling strength.

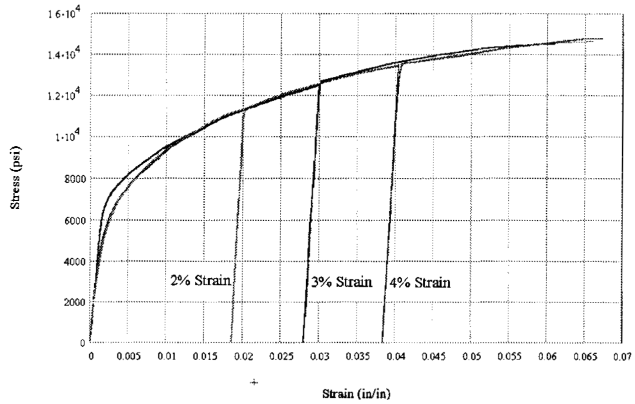

Figure 10. Strain hardening of 2-mil-thick aluminum sheet at different percent strain

After the coupon tests, self-rigidizable booms built with 2-mil-thick 1145-0 aluminum sheet were built, inflation deployed, inflation rigidized and buckling tested. Dimensions of these test booms are 2.5" in diameter and 22" in length. It is found after several tests that the failure mode was consistently local crippling and that the level of pressurization, i.e., degree of work hardening, had no direct relationship with the buckling capability of the booms. Sometimes a higher rigidization pressure would give lower buckling capability. The possible reason is that when subjected to internal pressure, the hoop stress in the boom is twice that of the axial stress. This results in more stretching in the hoop direction than in the axial direction. Tiny weaves on the aluminum sheet in the axial direction could have been introduced and adversely impacted the boom's capability to resist local crippling. In addition, it was found that high hoop stress induced by high pressure often caused failure in the seam and resulted in air leaks. To increase the degree of axial stretching without inducing excessive hoop stresses, an inside bladder with a diameter slightly smaller than that of the boom was added and inflated to pre-stretch the boom only in axial direction before buckling testing. Noticeable improvement in buckling capability was achieved by using this approach.

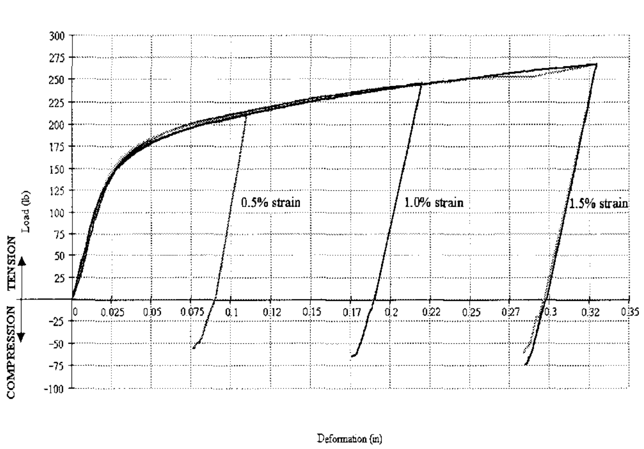

Figure 11. Buckling test results after booms were axial strain hardened—2-mil-thick 1145-0 aluminum sheet

Figure 11 gives buckling test results on aluminum booms that were axially pre-stretched. The first step of testing each boom was to apply 3 psi of pressure to remove any wrinkles that might have occurred during fabrication. The second step was to release the pressure, followed by using the internal bladder to axially stretch the boom to 0.5%, 1.0%, or 1.5% of elongation. The third step was to compressively load the boom to buckling. It can be concluded from Figure 11 that higher level of pre-stretching (i.e., higher pre-strain) consistently gives higher buckling capability (56 lbs with 0.5% pre-strain, 64 lbs with 1.0% pre-strain, and 74 lbs with 1.5% pre-strain).

For space applications aluminum laminates, instead of bare aluminum sheets, need to be used to construct self-rigidizable inflatable booms. The aluminum laminate used in this research was constructed with 3-mil-thick 1145-0 aluminum sheet with a 1-mil polyester film glued on each side. There are several reasons of using aluminum laminates instead of bare aluminum sheets. The first is that the glued-on polyester films behave like built-in bladders to reduce the possibility of gas leaking. The second reason is that many cracks were observed on the edge folding lines when the bare aluminum booms were flattened, rolled-up and deployed. These edge line cracks did not occur on the booms made of aluminum laminates. The third reason is that the inclusion of polyester films has shown to make the manufacturing and handling of the boom much easier.

A stress-strain curve of the selected aluminum laminate is shown in Figure 5. This aluminum laminate was used to build several test booms of 2.5" in diameter and 22" in length. Same test procedures used to test the 2-mil-thick bare aluminum boom, including the step of axially pre-staining by an internal bladder were used to perform the buckling load tests. Test results are shown in Figure 12. It can be observed from this figure that, 0.5% axial pre-strain gives maximum buckling load of 88 lbs. Without pre-strain, the 3-mil aluminum laminate booms give an average buckling capability of 77.3 lbs. However, lower buckling loads were obtained for booms with 1.0% pre-strain and 1.5% axial pre-strain. This led to the conclusion that for aluminum laminate booms, too much pre-strain could give lower buckling strength. This phenomenon was also reported by G. J. Friese, et al [10]. In their study, a test cylinder, made of polyester and aluminum layers of equal thickness, was pressurized far into the plastic region of the aluminum. The cylinder buckled as soon as the internal pressure was removed. This was due to the fact that after the laminate was stretched over certain percentage and the aluminum sheet had reached far into its plastic region, the polyester layers still remained to be completely elastic. After the tensioning force was released, the polyester layers would apply significantly high compressive stresses on the aluminum sheet and caused it to buckle. Therefore, it can be concluded that excessive pre-strain can reduce an aluminum laminate boom's buckling capability.

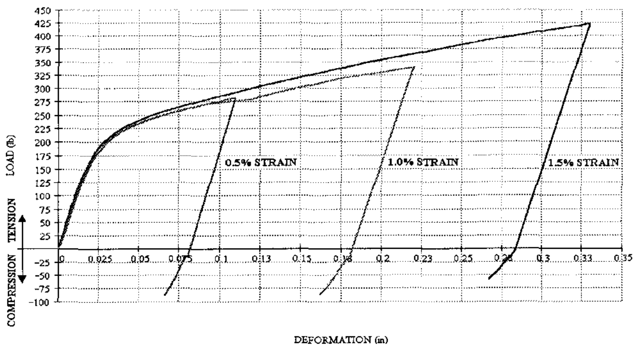

Figure 12. Buckling test results after booms were axially strain hardened—3-mil 1145-0 aluminum with 1-mil polyester films on both sides

5. Inflatable/Self-Rigidizable Booms—Carpenter-Tape Reinforced Aluminum Laminate Boom

An aluminum laminate boom's load-carrying capability is severely limited by certain design parameters such as material selection, wall thickness and the amount of pre-strain. In order to meet the load requirements of many future applications, a new type of aluminum laminate booms called the carpenter-tape-reinforced (CTR) aluminum laminate booms was developed during the course of this research effort. The CTR aluminum laminate booms not only have significantly improved buckling capability, but also preserve all major advantages of the non-reinforced aluminum laminate booms, including lightweight, reversibility for repeated ground testing and self-rigidizability.

The component materials of the CTR aluminum laminate booms studied by this research effort are:

(1) Aluminum laminate consisting of a 3-mil-thick 1145-0 aluminum sheet with 1-mil-thick polyester films glued on both sides
(2) Steel carpenter tapes (commercial grade)
(3) Kapton double-sided adhesive tapes for attaching the carpenter tapes to the inside of the boom
(4) Kapton single-sided adhesive tapes for bonding the axial seam
(5) Machined aluminum end caps

Figure 13 shows a cross-section of the CTR aluminum laminate boom. In order to keep the boom straight after inflation deployment, a dummy seam is also placed on the opposite location (180 degrees apart) of the real seam. The boom can be easily flattened, rolled-up, and deployed by a relatively low inflation pressure. The buckling capability of the CTR aluminum laminate booms is significantly improved mainly due to the high elasticity of modulus and curved cross-sectional profile of the carpenter tapes. It should be pointed out that the carpenter tapes are very effective in resisting inward buckling and the aluminum laminate wall is very stable in resisting outward buckling. Therefore, these two components effectively complement each other in resisting local crippling of the boom. In addition, unlike the non-reinforced aluminum laminate booms, a CTR aluminum laminate boom relies on the reinforcing tapes, not pre-strain induced by high internal pressure, to attain its post-deployment stiffness. The required inflation pressure for a CTR aluminum laminate boom is relatively low and that, in turn, reduces the load requirements for its seam.

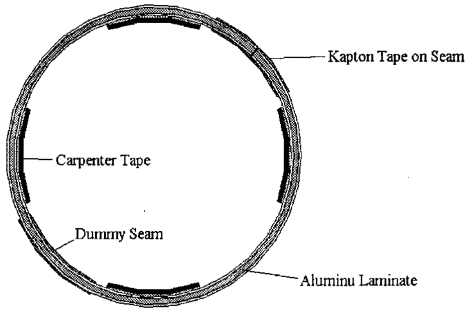

Figure 13. Cross-section of a CTR aluminum laminate boom

Seven CTR aluminum laminate test booms were fabricated and buckling tested. The boom dimensions are 3 inches in diameter and 16.4 ft. (5 meters) in length. The length of 5 meters was selected with the specific application to the full-size inflatable synthetic-aperture radars in mind. The average weight of these test booms (excluding the end caps) is 2 pounds each.

Figure 14 is a sketch of the test set-up. The test procedures consisted of the following steps:

(1) To place the portable test fixture in an upright position.
(2) To attach the test boom to the test fixture with ball bearings at the boom ends. The use of ball bearings is to simulate a pin-pin boundary condition.
(3) To turn on air supply and ensure that a 5-psi pressure is maintained. This is to remove any excessive wrinkles on the boom.
(4) To vent internal pressure from the boom.
(5) To apply compressive load on the boom by slowly turning the ball screw on the top end until buckling occurs.
(6) To record buckling load on the digital force gauge located at the lower end of the boom.

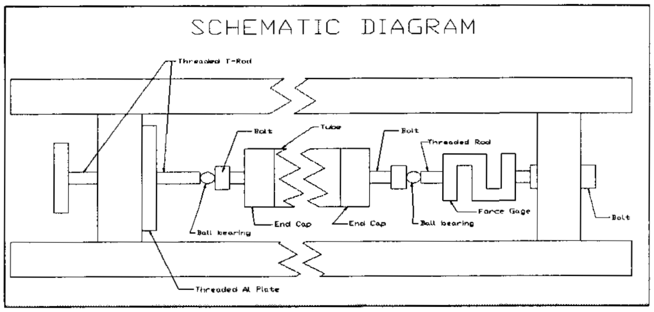

Figure 14. Schematic of test set up

Figure 15. Test scene

Figure 15 is a photo taken during one of the tests. Test results of the "first-time" buckling of the test booms are given in Table 1. Here "first-time" means that the test boom had not been rolled-up before being buckling tested.

Table 1. First time buckling test results

Boom number	1	2	3	4	5	6	7
Buckling load (lbs)	118.0	114.0	135.2	149.6	134.4	136.4	165.2
Buckling type	Euler	Euler	Euler	Euler	Euler	Euler	Euler

It can be seen from Table 1 that the buckling capabilities of the test booms are distributed in a range of 114 to 165 pounds. This may be due to: (a) some of the test booms had cross sections that were not perfectly circular, (b) some of the test booms tubes were not perfectly straight, and (c) possible imperfections on the surfaces of some of the test booms. Since the test booms were fabricated sequentially in the order of their designated numbers, it can also be observed from Table 1 that as more fabrication experience was gained, better booms with higher buckling strength were made.

Tests were also conducted to investigate the effect of stowage (rolled-up) to the buckling strength of the CTR aluminum booms. Details of these tests and test results are reported below.

Test Description:

1) Boom #3 and #4 were tested for the very first time. Both booms were inflated to 5 psi and maintained at that pressure for 5 minutes before testing. Buckling loads of 135.2 lbs for boom #3 and 149.6 lbs for boom #4 were obtained.
2) After the "first-time" buckling tests, both booms were flattened and tightly rolled up on mandrels. A 6.5"-diameter mandrel was used for boom #3 and a 12"-diameter mandrel was used for boom #4. Figure 16 shows the two mandrels with the rolled-up booms on them.

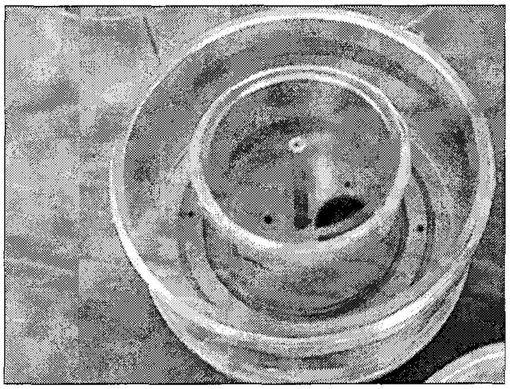

Figure 16. Flattened booms rolled-up on mandrels

3) After being stowed on the mandrels, Boom # 3 was first unrolled by its own stored energy. Figure 17 shows the boom half way deployed. The stored energy of the boom came from the strain energy stored in the steel carpenter tapes. This was sufficient to initiate self-deployment of the boom but not sufficient to complete full deployment. The self-deployment process was observed to be relatively slow and quite orderly.

Figure 17. Boom #3—half way deployed

4) After being inflated at 5 psi for 5 minutes, Boom #3 was buckling-tested twice. The first test resulted in 92.0 lbs and the second test resulted in 89.2 lbs. The boom was inflated at 5 psi for 5 minutes between these two tests.
5) After the two buckling tests, the boom was kept inflated at 5 psi for 2.25 hours. Then the buckling test was repeated and the result was 94.0 lbs. This indicated that keeping the boom pressurized for a longer time period would improve its buckling strength.
6) Boom #4 was unrolled and tested in the same way as Boom #3 (i.e., using above-described Steps 1 to 5). Buckling loads of 105.6 lbs and 101.6 lbs were recorded respectively.

Table 2 summarizes the test results. In this table, "inflation time" refers to the time that the booms were kept pressurized after inflation deployment.

Table 2. Post-stowage test results

Boom #	Test #	Buckling loads (lbs)	Inflation Time
3	1	135.2 (First Time)	5 minutes
3	2	92.0 (Rolled up)	5 minutes
3	3	89.2 (Rolled up)	5 minutes
3	4	94.0 (Rolled up)	135 minutes
4	5	149.6 (First Time)	5 minutes
4	6	105.6 (Rolled up)	5 minutes
4	7	101.6 (Rolled up)	5 minutes

It can be seen from Table 2 that the buckling load decreased each time we repeated the test on the same boom except for Test #4 on Boom#3 when it was kept pressurized for an relatively long period of time.

From these test data, we have following observations on stowage of the CTR aluminum laminate booms:

(a) After a boom being rolled up for stowage, its buckling strength is reduced. One possible explanation for the reduction is that during the roll-up process, the aluminum skin on the outside of the flat boom is being stretched while the skin on the inside of the boom is being compressed. After the boom is unrolled and inflated, the uniform internal pressure causes the stretched outside aluminum surface to wrinkle. These small wrinkles, which were observed on the test booms, might caused the reduction in the boom's buckling capability.
(b) Keeping the unrolled and deployed boom pressurized for longer time helps removing the wrinkles.
(c) The diameter of the mandrel appears to have only slight effect on the post-stowage buckling capability.

In parallel with buckling tests, finite element analysis was also performed to predict the "first-time" buckling load of CTR booms. The analysis model composed of 4802 nodes. 2364 laminate elements were used to simulate the carpenter tapes and the portions of the aluminum layer to which the tapes are glued. 2364 plate elements were used to simulate the rest of the aluminum layer. 96 solid elements were used to simulate end caps.

The buckling load derived from finite-element analysis is 167 lbs. with a failure mode of Euler buckling. Comparing to the maximum "first-time" buckling test result of 165.2 lbs. The percentage difference between the analytical prediction and test result is:

$$\zeta = \left(1 - \frac{\text{Test Result}}{\text{Analysis Result}}\right) = 1 - \frac{165.2}{167} = 1\%$$

6. CONCLUSION

A combined experiment and analytical study on four different designs of space inflatable booms was completed. These booms are (1) pressure-stabilized booms; (2) booms made of bare aluminum sheets, (3) aluminum laminate booms and (4) carpenter-tape-reinforced (CTR) aluminum laminate booms. Of these, the CTR aluminum laminate booms were shown to have the greatest potential in meeting the requirements of many future space mission applications, including high load-carrying capability. With the current design configuration, the CTR aluminum laminate booms are probably suitable only for certain, specific applications, such as the inflatable SAR that requires inflatable/rigidizable booms with less than 10 meters of unsupported length. Efforts are continuing at the Jet Propulsion Laboratory and California State University at Los Angeles to develop structural configurations and design improvements for self-rigidizable aluminum laminate booms of much longer lengths.

7. ACKNOWLEDGMENTS

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9. BIOGRAPHY

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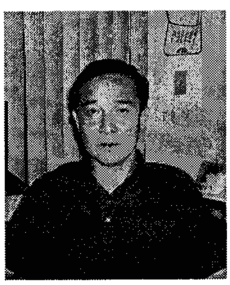

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